COMPARISION OF AlGaN/GaN AND AlGaAs/GaAs BASED HEMT DEVICE UNDER DOPING CONSIDERATION

Sana Firoz[1], **R.K. Chauhan**[2]
Department of Electronics and Communication Engineering
M.M.M. Engineering College
Gorakhpur-273010, INDIA
sana.firoz@gmail.com, rkchauhan27@gmail.com

Abstract

This paper present the behaviour and characteristics of various parameters of AlGaN/GaN based HEMT under the effect of doping. The impact of n-type doping material in carrier layer of AlGaN/GaN HEMT is significantly observed on threshold voltage, transconductance, maximum drain current, cutoff frequency and capacitance. Introducing the AlGaN instead of AlGaAs produces a very significant effect: Polarization. This causes accumulation of charge carriers easily on low doping. Apart from this the effect of doping is also considered on conventional AlGaAs/GaAs based HEMT. Using this method it can be observed that for the optimum doping the behaviour AlGaN/GaN based HEMT is more useful in terms of high power, high frequency response and lower parasitic capacitance.

Keywords

GaN HEMT, Carrier Layer, Polarization Effect, Capacitive effects.

I. INTRODUCTION

WIDE bandgap AlGaN/GaN high-electron mobility transistors (HEMTs) are emerging as excellent candidates for radio-frequency (RF) and microwave power amplifiers (PAs) because of their high-power-handling capabilities.[1]-[4]. Power amplifiers at RF and microwave frequencies find variety of application including cellular handset, WLAN, wireless broadband, satellite etc. The rapid growth of communication necessitated power amplifiers in high frequencies (1 GHz and 2 GHz) [5]. Power densities that are one order of magnitude higher than their silicon or GaAs counterparts have been demonstrated [6]. Earlier GaAs based HEMT were being used in power amplifier but due to small bandgap energy of GaAs the breakdown voltage is comparatively low as compare to GaN based HEMT and hence cannot be used when a very high power is required. The GaN HEMT is similar to a typical MESFET in that it is a three terminal device that utilizes the gate to control current flow [7]. While the MESFET is conceptually a very simple device, yielding sufficient performance well into the millimetre wave range, it does not unleash the full potential of group III-V semiconductor materials. The fact the free charge carriers and ionised dopants share the same space in MESFETs leads to a reduction of low field mobility through electrostatic fields.

Key factor of the application of Heterostructures in high speed devices lies in its internal mechanism viz the coulomb scattering and phonon scattering [9]. At room temperature (300 K) the scattering of electrons is mostly due to lattice vibrations-longitudinal optical phonons.

Coulomb scattering is due to electrostatic force between the mobile charge carriers and the fixed ionised atoms. In doped semiconductor the main source of fixed charge are the ionised doping atoms. Therefore the main electrostatic effect is needed to consider in n-channel MESFET is between the negatively charged electrons and the positively charged ionised donors.

While increasing the doping concentration the mobility limiting effect of coulomb scattering would become more pronounced. The physical location of free and fixed charge is the reason for the increased dominance of coulomb scattering hence it is better to physically separate free and fixed charge; the electrons and the ionised donors in an n-channel device. So doping plays a vital role in performance of HEMT Devices [9].

1.1AlGaN/GaN HEMT STRUCTURE: 2-DEG Formation & Polarization effect –

The basic concept in a HEMT (Fig.1) is the aligning of a wide and narrow bandgap semiconductor adjacent to each other to form a heterojunction. The carriers from a doped wide energy gap material (AlGaN) diffuse to the narrow band gap materials (GaN) where a dense 2-DEG (Two Dimensional Electron Gas) is formed in the GaN side but close to the boundary with AlGaN. The unique feature of the HEMT is channel formation from carriers accumulated along a grossly asymmetric heterojunction, i.e. a junction between a heavily doped high bandgap and a lightly doped low bandgap region [7].

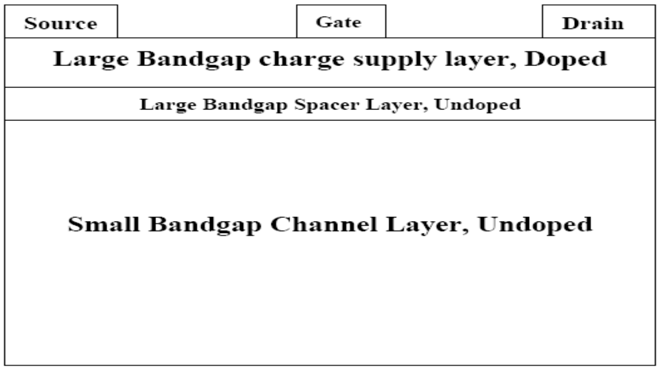

Fig 1.Layered structure of High Electron Mobility Transistor.

To achieve proper operation of the device, the barrier layer $Al_xGa_{1-x}N$ must be at a higher energy level than the conduction band of the GaN channel layer. This conduction band offset transfers electrons from the barrier layer to the channel layer. The electrons that are transferred are confined to a small region in the channel layer near the hetero-interface. This layer is called the 2DEG (Fig.2) and a defining characteristic of the HEMT. There are many factors that determine the quality of the 2DEG. The factors involved in the development of the 2DEG are type of substrate, growing method, and level of doping of the carrier supply layer [10].

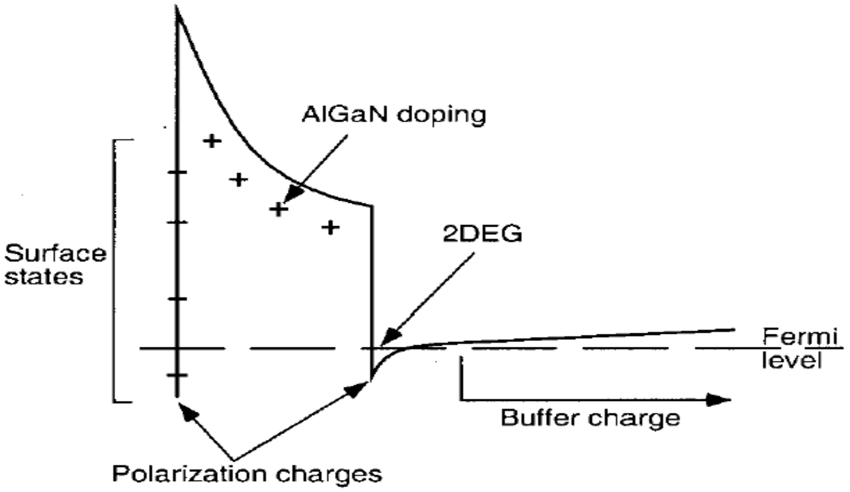

Fig 2.Energy band diagram showing 2DEG formation.

The Fermi energy level of this thin layer is above the conduction band thereby making the channel highly conductive. The ratio of aluminium to gallium is AlGaN is typically 30% Al and 70% Ga. The resulting compound has a higher energy band gap and different material properties from GaN. The structure of HEMT is formed by various layers viz nucleation, buffer, spacer, carrier supply, barrier and cap layers.

In a typically doped AlGaN/GaN HEMT structure, AlGaN donor (carrier supply) layer supplies electrons to the 2DEG. The 2DEG is formed at the AlGaN/GaN interface even if all the layers are grown without intentional doping. In fact the contribution of the doping to the 2DEG sheet carriers concentration is reported to be less than 10% due to stronger piezoelectric effect in the material system.

In this paper impact of n-type doping in AlGaN is studied under the performance parameters like threshold voltage, cutoff frequency, capacitive effects and drain current. ATLAS Device simulator is used in this analysis.

Nitride materials (GaN, AlN, InN and their ternaries) exist in two crystal structures: Wurtzite(WZ), and Zinc-Blende (ZB). Wurtzite is the most common crystal structure for nitride materials used in electronic devices. It is a structure of hexagonal crystal systems where tetrahedral coordinated Ga (Al, In) and N atoms are stacked in an ABABAB fashion , Due to the non-centro-symmetric nature of the Wurtzite structure, a nonzero volume dipole moment exists in the nitride crystal when there is no external strain or electric field, which results in spontaneous polarization in nitride materials. Furthermore, there are nonzero piezoelectric moduli when the wurtzite structure nitride materials are stressed along [0001] direction, resulting in piezoelectric effects. These piezoelectric effects and the difference in spontaneous polarization between AlGaN and GaN cause polarization charges and fields in AlGaN/GaN HFETs.

As a result of polarization effects, the polarization induced positive electrostatic charges are present at the AlGaN/GaN hetero-interface, while corresponding negative electrostatic charges are present at the AlGaN surface. These charges also result in an electric field. The Charge density and the internal electric field in the AlGaN layer are determined by the sum of the difference in the spontaneous polarization between AlGaN and GaN, and the Piezoelectric polarization resulting from the strain [8]. The polarization induced charges present in the hetero-interface induce a layer of two dimensional electron gas (2DEG) in the GaN layer immediately under the interface causing significant effects on current and other parameters.

II. RESULTS AND DISCUSSION

This section will outline basic HEMT parameters. The primary operating parameters dealing with high power HEMT operations are the threshold voltage (V_t), the transconductance (g_m), the maximum drain current (I_D),the unity gain cutoff frequency (f_t), and parasitic capacitances [7].

2.1 Threshold Voltage

Field effect transistor is a voltage controlled device. The current between two terminals is controlled by the applied voltage on the third terminal. The minimum gate voltage which should be applied in order to form a channel of unipolar charge carrier so that current may flow from drain to source is known as threshold voltage. HEMT is an n channel device hence positive voltage is to be applied to form 2DEG.

Unlike traditional MOS devices, the charge flowing in a HEMT device is normally confined to the 2DEG and changed by the gate voltage. When a gate voltage is applied to the device, the sheet charge concentration (n_s) is changed proportionally to gate voltage and is given by

$$n_s = \frac{\varepsilon_i}{q}\frac{(V_g - V_t)}{(di + \Delta d)} \qquad [1]$$

Where ε_i and d_i are the dielectric permeability and the thickness of the wide bandgap semiconductor, respectively, and $\Delta\, d$ can be interpreted as the effective thickness of the 2DEG [7]. The threshold voltage is an important parameter because it is a measure of when the HEMT device will begin conducting. V_t can be expressed as:

$$V_T = \emptyset_B - \Delta E_C - \frac{qN_D}{2\varepsilon_i} d^2 \qquad [2]$$

Where φ_B is the gate Schottky-barrier height and ΔE_C is the change in the conduction band at the heterojunction and N_D is the background doping.

For a device and fixed bias voltage the Schottky-barrier height, dielectric constant and other parameter can be considered as constant hence threshold voltage will decrease when doping increases and N_D will be the dominant factor.

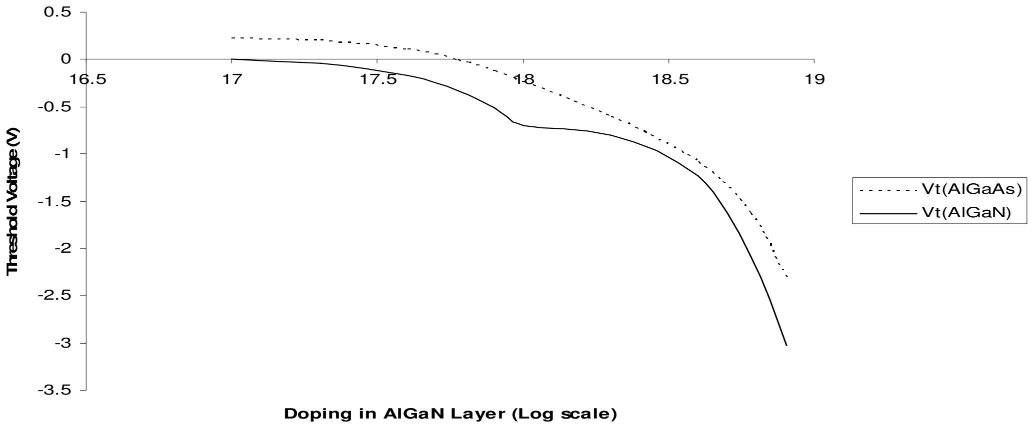

Fig 3.Threshold Variation of GaAs and GaN Based HEMT Devices against Doping Level in Carrier layer.

Fig.3 is the plot between threshold voltage and Doping (Log Scale), this clearly shows that the device can be activated even on more negative potential because accumulation of charge carriers due to high doping. This result can be justified by the equation 1, which shows that at more negative V_t, sheet charge density will be high enough. Fluctuation of V_t significantly increases for higher doping region (10^{19} Atoms/cc). HEMT Device is Gate controlled only for optimum doping level ($<10^{18}$ Atoms/cc), beyond this doping level threshold voltage drastically change in negative values. Due to the Polarization effect of Nitride there is accumulation of Charge carriers at AlGaN/GaN interface. So in comparison to AlGaN/GaN the threshold voltage of AlGaAs/GaAs HEMT is slightly less negative due to lack of polarization.

2.2 Maximum drain current:

Maximum drain current is important measures of a HEMT device when utilized as a power amplifier. For long channel devices (Lg> 0.25µm), I_{DSat} can be expressed the same as a standard MOSFET:

—— [3]

Where µ is the carrier mobility, C is the gate capacitance, W is the gate width, and L is the gate length.

The consequent effect of polarization on threshold voltage can be easily seen on maximum drain current. From the above expression the maximum drain current depends upon on mobility and threshold voltage at a fixed gate voltage.Though the mobilty of charge carriers decreases as the doping increases but the threshold voltage further increases quadratically hence the current increases drastically at higher concentration(10^{18} Atoms/cc). As compare to AlGaN/GaN HEMT the current is small in AlGaAs/GaAs HEMT .Hence it is justified that GaN HEMT can be used for high power application without increasing doping level as comparision to GaAs HEMT.

2.3 Parsitic Effects & Cutoff Frequency:

The simplified cutoff frequency f_T can be expressed as

$$f_T = \frac{g_m}{2\pi(C_{gs}+C_{gd})}. \qquad [4]$$

Transconductance signifies that how the drain current will change with a change in the gate voltage. Mathematically, transconductance is defined as

$$g_m = \frac{\partial I_D}{\partial V_G}\bigg|_{V_{D=Const.}} = \frac{\mu C_{gs}}{L} W(V_g - V_t) \qquad [5]$$

Transconductance is dependent on mobility and Threshold Voltage which consiquently depends on AlGaN Doping. So as the doping increases transconductance is increases but at the higher doping level mobility plays a vital role. In our analysis FLDMOB,CONMOB(Field and Concentration Dependent Mobility) is used. So for high Doping region (10^{19} Atoms/cc) mobility is degraded. So it is proposed that loss of mobility with increasing carrier concentration is due to the effect of the interface roughness, which is similar to the explanation of gm degradation at high doping level [8]. This behavior affects the frequency performance and linearity of the device. The nonlinear source resistance due to the on-set of space charge limited current transport condition existing in AlGaN/GaN HFETs is the origin of the extrinsic gm and Cgs degradation at high doping [12]. Due to the polarization effects Transconductance is not significantly changed (in comparison to GaAs HEMT).There is a increment in field due to polarization effects by which mobility and capacitance decreases. In the case of Transconductance, threshold voltage dependency does not play a vital role due to linear dependency (as compare to the drain current quadratically depend on threshold voltage).Fig.5 justifies the above discussion on polarization effect.

At first the magnitude of Capacitance increases with doping. After critical point, the magnitude of Capacitance begins to decrease with doping. Extrinsic capacitance at first increases as doping increases, following the normal FET behaviour until the space charge effects. Capacitance then decreases as doping increases because the source resistance increases rapidly once the space-charge effects occur. In order to verify that the onset of the space charge effect is related to the background charge, device with different doping levels were simulated and their capacitive behavior is analysed. The comparison indicates that for less 2DEG concentration where background charge density is lower, the magnitude of Cgs begins to decrease at lower drain current, representing that the critical current density for the onset of the space-charge effects decreases [8].

Fig.6 shows the verification of above discussed theroies regarding capacitance.Due to lower dielectric constant of GaN Capacitance is low enough as compare to GaAs HEMT to overcome the effect of sheet charge density. Dielectric constant is the dominant factor though the sheet charges density increses with doping as well as polarization effect is also responsible for high sheet charge density.

Now , considering the transconductance and capacitive variation cutoff frequency varied as accordannce to the inverse propotionality of capacitance and linear relationship of transconductance. Fig.7 shows the comparison of two devices viz.GaAs & GaN based. Polarzation and high doping effect on mobility causes degradaton in cut fof frequency.

It can be seen that the f_T is lower for high doping levels. Therefore the frequency performance of the device is also limited by the nonlinear behavior of the source resistance.

	Length(um)	**Height(um)**	**Doping(Atoms/cc)**
Device	0.75	0.22	-
Channel	0.65	-	10^{17} -10^{19}
Drain	0.05	0.02	10^{18}
Source	0.05	0.02	10^{18}

Table 1. structure of using hemt device for analysis

In comparison to GaAs HEMT GaN based HEMT devices show different characteristic performance under doping consideration. Due to heavy doping and polarization effect threshold voltage changes abruptly which signifies the accumulation of charge carriers at the AlGaN/GaN interface. Again the effect of polarization can be analysed on maximum drain current, it increases as the doping level increases. Using nitride based HEMT transconductance is not significantly changed as compared to GaAs HEMT. The fluctuation in capacitance is not considerable in GaN HEMT devices though the capacitance is much influenced by doping in context to GaAs HEMT. In spite of same variation in doping the cutoff frequency is considerably high in GaN HEMT signifies high frequency response.

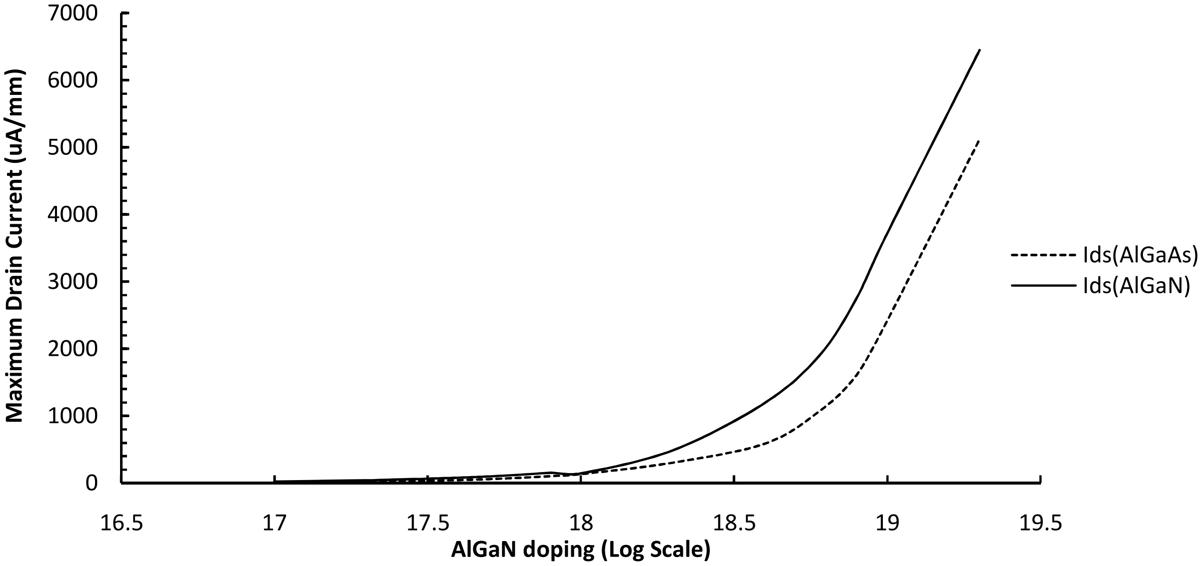

Fig 4.Maximum Drain Current variation of GaAs and GaN Based HEMT Devices against Doping Level in Carrier layer.

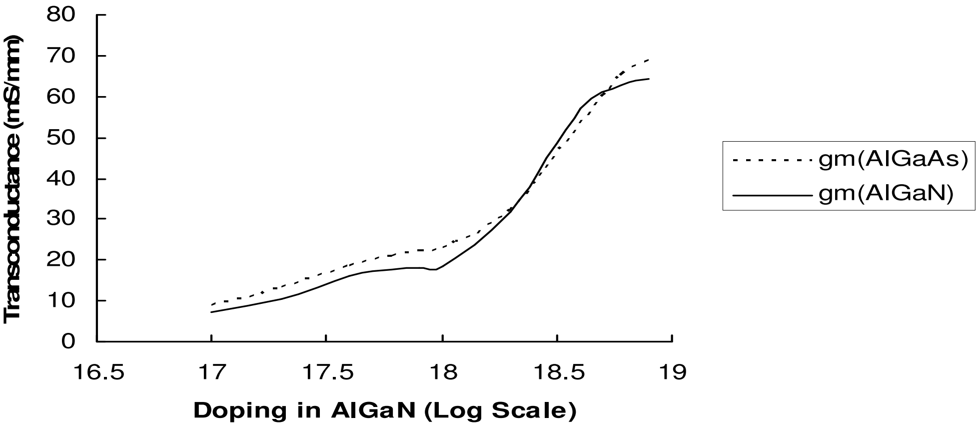

Fig 5.Transconductance variation of GaAs and GaN Based HEMT Devices against Doping Level in Carrier layer.

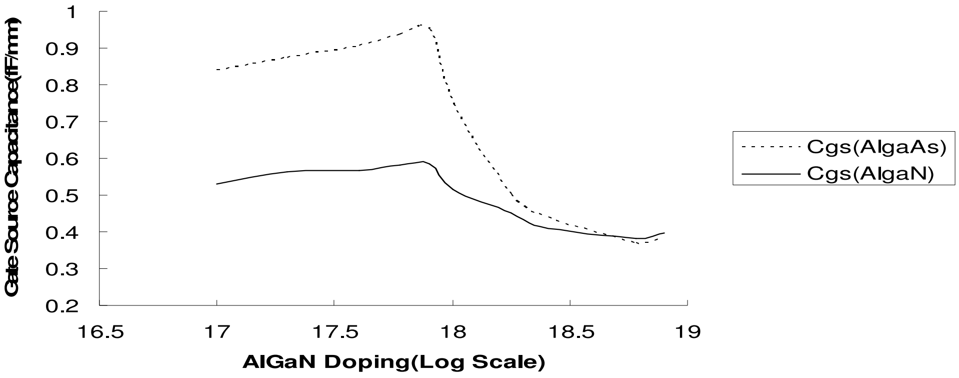

Fig 6.Gate Capacitance variation of GaAs and GaN Based HEMT Devices against Doping Level in Carrier layer.

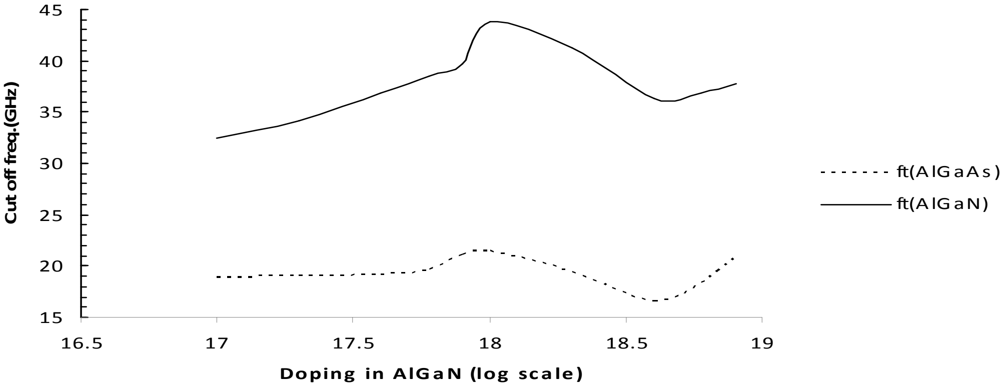

Fig 7.Cut off frequency variation of GaAs and GaN Based HEMT Devices against Doping Level in Carrier layer.

III. CONCLUSION

For high speed and power application GaN Based HEMT devices is superior to GaAs based devices. Higher doping can be resulted into high drain current but leads to lower cutoff frequency. More ever threshold voltage decreases in negative value at higher doping level. Considering all the theories discussed on polarization effects, a conclusion can be made that 10^{18} Atom/cc is the optimum doping level.

ACKNOWLEDGMENT

We are greatly indebted to our project guide Dr. R. K. Chauhan, Department of Electronics and Communication Engineering, M.M.M. Engineering College, Gorakhpur; who has not only suggested this topic, provided the perfect guidance, but also has always kept our spirit high, by his invaluable discussions, feedbacks and constant encouragement. He was a source of inspiration to us all along. Thank you sir, for your parent like support, throughout the year. We are also very grateful to our head of department Dr. C.B. Tripathi for his encouragement and inspiration. It was a memorable group task, which we enjoyed very much, and learnt many things right from beginning. We would also like to thank our friends for their useful contribution towards the successful completion of our present project work.

REFERENCES

[1] Y. Ando, Y. Okamoto, H. Miyamoto, T. Nakayama, T. Inoue, and M. Kuzuhara, "10-W/mm AlGaN-GaN HFET with a field modulating plate," IEEE Electron Device Lett., vol. 24, no. 5, pp. 289–291, May 2003.

[2] K. Joshin, T. Kikkawa, H. Hayashi, S. Yokogawa, M. Yokoyama, N. Adachi, and M. Takikawa, "A 174 W high-efficiency GaN HEMT power amplifier for W-CDMA base station applications," in IEDM Tech. Dig., Dec. 2003, pp. 983–985.

[3] J. W. Johnson, E. L. Piner, A. Vescan, R. Therrien, P. Rajagopal, J. C. Roberts, J. D. Brown, S. Singhal, and K. J. Linthicum, "12 W/mm AlGaN–GaN HFETs on silicon substrates," IEEE Electron Device Lett., vol. 25, no. 7, pp. 459–461, Jul. 2004.

[4] Y. F.Wu, A. Saxler,M.Moore, R. P. Smith, S. Sheppard, P.M. Chavarkar, T. Wisleder, U. K. Mishra, and P. Parikh, "30-W/mm GaN HEMTs by field plate optimization," IEEE Electron Device Lett., vol. 25, no. 3, pp. 117–119, Mar. 2004.

[5] E.T Heyen, "Secure Mobile Solution- Poised for Profitable Growth,"3GSM Presentation, Infenion , pp. 11,Feb.2004

[6] W. Lu, V. Kumar, E. L. Piner, and I. Adesida, "DC, RF, and microwave noise performance of AlGaN-GaN field effect transistors dependence of aluminum concentration," IEEE Trans. Electron Devices, vol. 50, no. 4, pp. 1069–1074, Apr. 2003.

[7] S. Tzeng, "Low-Frequency Noise Sources in III-V Semiconductor Heterostructures," 2004.

[8]. E. T. Yu and e. O. Manasreh, "Spontaneous and piezoelectric polarization in nitride heterostructures.," in III-V Nitride Semiconductors: Applications and Devices (Optoelectronic Properties of Semiconductors and Superlattices, 16): Taylor & Francis, 2003.

[9]. J. M. Barker, D. K. Ferry, S. M. Goodnick, D. D. Koleske, A. Allerman, and R. J. Shul, "High field transport in GaN/AlGaN heterostructures," Journal of Vacuum Science & Technology B, vol. 22, pp. 2045-2050, 2004.

[10]. P. Javorka, "Fabrication and Characterization of AlGaN/GaN High Electron Mobility Transistors." 2004.

[11] O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, "Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaN/GaN heterostructures," Journal of Applied Physics, vol. 85, pp. 3222-3233, 1999.

[12] R. J. Trew, L. Yueying, L. Bilbro, Weiwei Kuang, R. Vetury, and J. B. Shealy, "Nonlinear source resistance in high-voltage microwave AlGaN/GaN HFETs," Microwave Theory and Techniques, IEEE Transactions on, vol. 54, pp. 2061-2067, 2006.

Author biography

Sana Firoz received the bachelor of technology degree in electronics and communication engineering (with excellent academic record) from Madan Mohan Malviya Engineering College Gorakhpur in 2010.currently seeking the opportunity for doing Ph.D from a best recognized college of India. It is her first paper based on her final year project. Her main research interests are in RF and microwave control devices and semiconductor components such as p-i-n diodes, MESFET's, heterojunction FETs (HFETs)

Dr R.K Chauhan did his B.Tech in Electronics & Communication Engineering, G.B.P.U.A.T – Pantnagar, India. He completed M.E. in Control &Instrumentation, MNREC-Allahabad University (presently MNNIT-Allahabad) and received the Ph.D in Electronics Engineering, "Effect of Ionizing Radiation on Some MOS based Devices" Department of Electronics Engineering, IT-BHU, Varanasi, India(April, 2002).He is currently a Associate professor with the Department of electronics and communication Engineering, Madan Mohan Malviya Engineering College Gorakhpur. He is Reviewer of Microelectronics Journal and Selected as one of the top 100 Engineers of 2010 by International Biographical Centre, Cambridge, England. He achieved Best Paper award at the International Conference IICT-2007 held at DIT, Dehradun from 27-29 July.